Naval Surface Warfare Center
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NSWCCD-CISD–2008/006 July 2008

Ship Systems Integration & Design Department
Technical Report

Inflatable Causeway (MOSES) Demonstration

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NSWCCD-CISD-2008-006

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
25-Jul-2008

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
19-May-2008 – 25-Jul-2008

4. TITLE AND SUBTITLE
Inflatable Causeway (MOSES) Demonstration

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Brenton Mallen and Benjamin Testerman

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
Naval Surface Warfare Center
Carderock Division
9500 Macarthur Boulevard
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-CISD-2008/006

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Chief of Naval Research
One Liberty Center
875 North Randolph Street,
Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A lightweight, rapidly deployable causeway concept consisting of a pressurized water-filled bag and an air beam supported reservoir has been developed. Small scale prototypes of the bag and air beam systems were tested to demonstrate seakeeping characteristics of the causeway and the capability of the air beams to deploy the system.. The seakeeping tests were focused on roadway motions and the presence of green water on the roadway.

15. SUBJECT TERMS
Inflatable structure, causeway, air beam, pressurized, rapidly deployable, logistics, Moses, CISD, JLOTS, Joint Logistics Over the Shore, logistics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	27	Colen Kennell
					19b. TELEPHONE NUMBER *(include area code)* 301-227-5468

Abstract

A lightweight, rapidly deployable causeway is of interest to the United States Navy because it will allow for an easily deployable, transportable, recoverable and storable roadway from ship to shore. In 2007, the challenge of designing such a causeway was undertaken by a Center of Innovation in Ship Design project team and the preliminary design phase was completed. The resulting design became known as MOSES. The design is described as an oval-shaped, tapered-end, water-filled bag pressurized to expand above the surrounding water line, becoming rigid and negatively buoyant. To pressurize the bag, air-beam supported walls that shield the vehicles from the waves act as a reservoir to hold water and create the pressure head. The 2007 MOSES project proved that a flexible material used in the fabrication of the roadway can be made rigid enough to support the weight of cargo being offloaded from a ship.

The aim of the 2008 MOSES project is to continue to demonstrate the feasibility of the MOSES concept. The two main feasibility demonstration issues, deployment of MOSES via air-beams and seakeeping characteristics of the MOSES bag are the focus for this year's project. Construction and testing to validate these systems is the next milestone in proving the MOSES. The 2008 MOSES project tested these two components through two models: a water based model, focusing on roadway motions and green water presence on the roadway, and a deployment model demonstrating the operation of the air beam structure technology within the reservoir walls.

Acknowledgements

The accomplishments of this year's work have built upon the foundation set forth by the MOSES design team of 2007, Kent Dickens and Philip Rosen. The current opportunity to further advance the MOSES concept was offered by the National Research Enterprise Intern Program, which is sponsored by the Office of Naval Research. All research took place at the Naval Surface Warfare Center Carderock Division in the Center for Innovation in Ship Design.

The intern team consisted of:

Brenton Mallen

Benjamin Testerman

A special thanks to:

- Sarah Cole for her constant support and encouragement throughout the entire project.
- Lieutenant Commander and Mrs. Mark Read for all their help with the construction without which the deployment model would not have been possible.
- Dr. Colen Kennell for his input and his help gathering materials for construction.
- Jim Hickok for is invaluable support with sensor set-up and data collection during the experiment phase of the project.

Executive Summary

MOSES is a design concept that was created by the CISD 2007 MOSES Project team and was selected. MOSES is an inflatable causeway system that is designed as a roadway allowing vehicles to be driven from ship to shore. What makes MOSES different from other causeways in use today is that it is lightweight and rapidly deployable. MOSES is essentially a large pressurized fabric bag, or bladder, that is filled with seawater and which has a flat surface on top so that a planked roadway system can be laid out.

The MOSES causeway is designed to rest on the sea floor, which adds to its stability, and allows it to remain in place during high sea state conditions. The bag is also tapered to contour to the seafloor so it can maintain a roadway surface one meter above the sea level. In order for MOSES to rest on the seafloor, a large downward force needs to be generated. The reservoirs that are built into the walls of the bag contain water that creates this negative buoyancy.

The walls also serve two other purposes. The first is that the walls protect the roadway, and the traversing vehicles, from surf that could cause damage to the vehicles and instability in the bag. The second purpose of the walls is that they act as a reservoir for water that creates a pressure head increasing the pressure in the bag and to increase rigidity. The frame of the walls is created by using an air beam structure system, which not only holds the wall upright, but also provides for the deployment of the causeway. Two models were constructed to simulate the deployment of the causeway and to demonstrate the stability of the bag within the surf.

MOSES is stored in a rolled up configuration, which makes it easy for storage and transportation. In order to unroll the bag, air is pumped into the air beam system. Through a proof of concept model, it was shown that air pressure alone is enough to unroll the causeway. Once the walls are inflated and the causeway unrolled, water is pumped into the bag. Once the causeway is deployed, it must withstand the forces equivalent to sea state 4. A model was constructed and placed in the 140-foot basin to observe the effects of the surf on the causeway. The next step in refining and validating the MOSES concept has been taken in this project, but further research is needed to develop this innovative concept into a practical operational system.

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1.0 Introduct ion

In the summer of 2007, the task of developing a concept design for the project known as MOSES was undertaken. The work completed in 2007 left a concept design, shown in Figure 1, which required validation. This work has been continued in the 2008 Moses project, focusing on demonstrating the key concepts generated from the previous summer's study.

1.1 2007 Effort

Current causeway systems in use in the military consist of large rigid structures. These structures are frequently heavy, as well as difficult and time consuming to assemble and install. The objective of the 2007 concept work was to "develop a lightweight, rapidly deployable 'causeway' concept to enable movement of wheeled and tracked military vehicles from shallow draft ships through the surf zone to shore without wetting the vehicles."

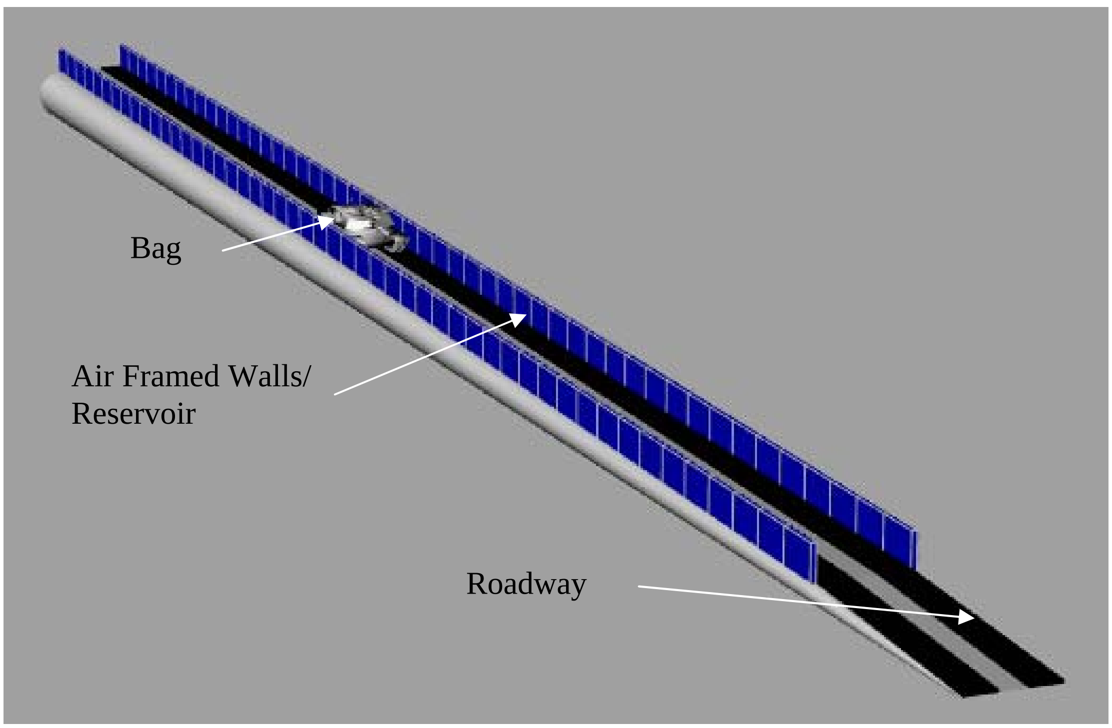


Figure 1: Moses 2007 Final Design

Requirements

The following table lists the notional requirements developed by the 2007 MOSES project:

	Threshold	Goal
Operational Sea State	2	4
Water depth (m)	1	2
Beach gradient	50:1	30:1
Deployment time (hr)	6	2
Vehicle transfer speed (mph)	5	10
Stowage volume (cu m)	~80	~40
Useable life (# of deployments)	20	40
Useable life (yrs)	5	10

Table 1: 2007 Requirements

2007 Design

The concept design generated in 2007 consisted of the following three parts. First a water filled fabric bag to be used as the roadway base. Second sidewall reservoirs designed to generate a pressure head in the bag below while being supported by an air beam structure as shown in Figure 2. Finally a rigid roadway structure is used to protect the bag from damage.

Water Filled Fabric Bag

The water filled fabric bag is the base for the causeway. The design allows the bag to rest on the ocean floor, while keeping the roadway on the bag's surface above sea level. When pressurized, the bag becomes rigid, allowing it to support vehicles on the roadway.

Sidewalls/Reservoir

In order to meet the 2007 objective of transferring vehicles from ship to shore without contact with the water, sidewalls were added to the bag. The sidewalls serve the following purpose support a reservoir which generates a pressure head to maintain rigidity in the bag below and deflect waves from the roadway. In order to support the reservoir, the concept of an air beam structure was developed. Air beam systems have been proven in the past for their ability to support large amounts of weight. Additionally, the air beams would be used to deploy the system from its furled state.

Roadway

The final component of the design is the roadway planking. The planking system was designed to be mounted on the surface of the bag to support the tanks and equipment traversing above and prevent the bag fabric from being damaged.

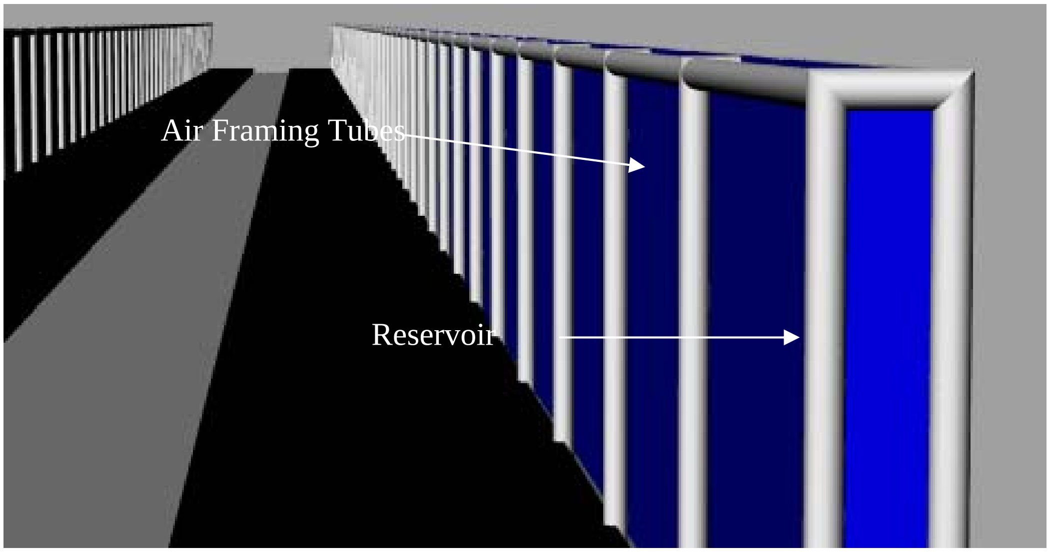


Figure 2: Moses 2007 Final Design

2007 Demonstrator

At the completion of the 2007 MOSES project, a 1/20th scale model was constructed to demonstrate the ability of the pressurized bag to support the necessary weight of equipment on top. MOSES, when filled, can support a significant amount of weight, as shown in Figure 3, without deformation of the bag.

Figure 3: 2007 MOSES Demonstrator Model

2.0 2008 Effort

The next step in development of the 2007 design concept work was to demonstrate the feasibility of the concept. The initial objective for the 2008 Moses project, included in Appendix A, was to "identify the motions and deformations of a MOSES prototype model under surf zone conditions when loaded with Main Battle Tanks". After initial analysis, it quickly became apparent that surface motions on the bag were not the only concern for the project. The primary focus of the project became proof of the overall system with its various components.

Initial work in 2008 consisted of brainstorming which components of the concept needed further investigation. The results of this analysis are included in Appendix B. The critical systems selected for analysis were deployment, motions, and deformations of the bag. The main concerns with the deployment system were whether applying air pressure to the beams would unroll the bag and if the pressure would be sufficient for the walls to erect themselves in the process. A plywood beach constructed in the 140-foot basin was used to test the model in order to place it in a scaled surf zone, and the motions associated with the waves impacting the bag were measured and observed.

2.1 Model Testing Plan

A model testing program was developed in order to achieve the objectives set forth above. Due to scaling limitations of the various systems, a two model program was adopted. The two models are a water based model and a deployment model.

Water-Based Model

The purpose of the water based model was to observe the bag motions and deflections, the effect of vehicles moving on the surface of the bag, and the ability of the walls to deflect the water. Quantitative testing was conducted in the 140' basin at NSWCCD. Outdoor testing, completed first, allowed for the development of methods for inflating the bag, and improved the efficiency of tank testing time. Appendix F includes the three testing conditions, which were determined necessary to achieve the above objectives. They are in-line waves, oblique seas, and perpendicular seas. The fabricated model can be seen in Figure 4. Also to be noted through these tests were the effects of a non-uniform sea floor, and vehicle motions on the bag surface.

Figure 4: 2008 MOSES Water-Based Model

Model

The water based model was made to 1/25th scale. This decision was primarily controlled by the limit of the 3" maximum wave height that can be generated in the 140' basin. While the model cross section was scaled to 1/25, the scaled length was cut in half to a length of approximately 10'. The decision to cut the length in half came as a result of the desire to fit the model at large angles in the model basin which is approximately 10' wide.

Environment

Initial plans were to test the model in scaled sea state 4 conditions. However, the wavemaker in the 140' basin could not generate the required irregular waves. Therefore, scaled regular waves matching the significant wave height and period of a sea state 4 were used. The full-scale wave height scaled linearly from λ_p=6.2' yielded λ_m=~3". Similarly the wave period was scaled with the square root of the linear scaling factor from T_p=8.8 sec to T_m=1.76 sec.

Using a plywood beach (Appendix G) with a slope of 1:20, the uniform cross section of the bag was placed so that a section located approximately 2 feet from the end of the bag was sitting in 6 inches of water, reflecting the designed waterline for the MOSES model. This point was the reference point for all measurements taken. Crossbow CXL-GP Series Accelerometers were used to measure accelerations on the surface of the bag as it encountered waves. Sinusoidal waves of 3" height and 1.76 second period were generated in the basin.

In-Line Testing

The first set of tests was designed to observe the effect of waves moving in line with the bag and the movement of the roadway associated with these waves. This demonstrated the highest potential for a "water bed effect" motion caused by changes in pressure on the surface of the water filled fabric.

Oblique Angles

The second set of tests was designed to observe the ability of the bag to resist sideways motion caused by waves crashing at oblique angles to the bag. This test was designed to prove the ability of the sidewalls to prevent seawater wetting the cargo on the causeway. The orientation of the model can be seen in Figure 5.

Figure 5: Water Based Model at 40°

Perpendicular Seas

The final arrangement set the bag perpendicular to the travel of the waves. This experiment was designed to show the ability of the bag to remain anchored in place in the most severe condition with waves crashing on its side. For this experiment, capacitance probes were placed fore and aft of the bag to demonstrate the ability of the water filled fabric to attenuate waves. The orientation of the model can be seen in Figure 6.

Figure 6: Water Based Model at 90°

Additional Observations

Throughout the above tests, additional observations were made to see how rigid water filled bags behaved when encountering discontinuities in the sea floor. For this experiment, the bag was inflated over non-continuous slopes including the use of large obstacles such as a log or rock lying on the bottom in the surf zone.

The final observation was to demonstrate the effect of a vehicle moving on the surface of the bag. This test was useful in both indicating how much movement vehicles would experience when traversing the causeway as well as the "water-bed effect" in the bag caused by the vehicles movement. The scaled weight of a Main Battle Tank was calculated to be 8 lbs at the 1/25 scale. A model truck was used to represent the tank traversing the causeway.

Deployment Model

Beyond testing the water based motions model, the second key area of concern was the sidewall air beam. With a scale of 1/25, it was difficult to fabricate effective air beams with the available fabrication capability. Therefore, the air beam fabrication was completed at a scale of 9/50. This scaling allowed the use of ½" copper pipefittings in the joints of the system. The system can be seen in Figure 7.

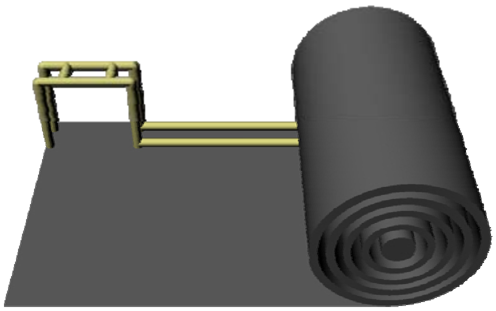


Figure 7: 2008 MOSES Deployment Model

With the fabrication of the air tube as the controlling factor in the construction of the deployment model, it became apparent that constructing an effective and reliable air beam system would be challenging. Several fabrication methods were explored; however, creating a reliable consistent seal at the copper joints proved difficult. By trial and error, a fabrication method was found that produced a model that was reliable enough for testing. The first successful model can be seen in Figure 8.

The air beams are constructed of a bicycle tire tube that has its expansion constricted by a duct tape tube. The duct tape tube is lined with painter's plastic in order to add rigidity and ease fabrication. The rubber bike tubes were secured to the copper couplings by the use of electrical tape for its stretching property, which resulted in a decent seal.

There were two conditions in which to examine the air beam walls. One was the physical act of unrolling the system and the other was the capability of the walls to stand erect when the bag was fully inflated and pressurized. Therefore, two tests were conducted to address the two conditions.

In the unrolling test, the air beam wall model was attached to a long piece of vinyl. At the end of this piece of vinyl, there was a weight used to simulate the scaled weight of the system when it is rolled up. The system was rolled up tightly and then air was applied to the air beams to observe if the system unrolled. The air beams were inflated and rigid, but not upright since they were not firmly attached at their base.

The second model simulated how the air beam walls react when attached to a solid foundation. This was accomplished by attaching the base of the walls to a plank of wood. Air was added to the tubes during testing and the results were recorded.

Figure 8: Air Beam Structural Model

2.2 Model Testing Results

Water-Based Model

The first set of tests conducted on the model was in-line with waves. As test runs were conducted, it was observed that the beach below the model was flexing as waves crashed on it. In order to account for the accelerations caused by the beach, an accelerometer was placed on the beach adjacent to the bag. Results of a representative run in this configuration can be seen in Figure 9. Additional plots from water-based tests are in Appendix E.

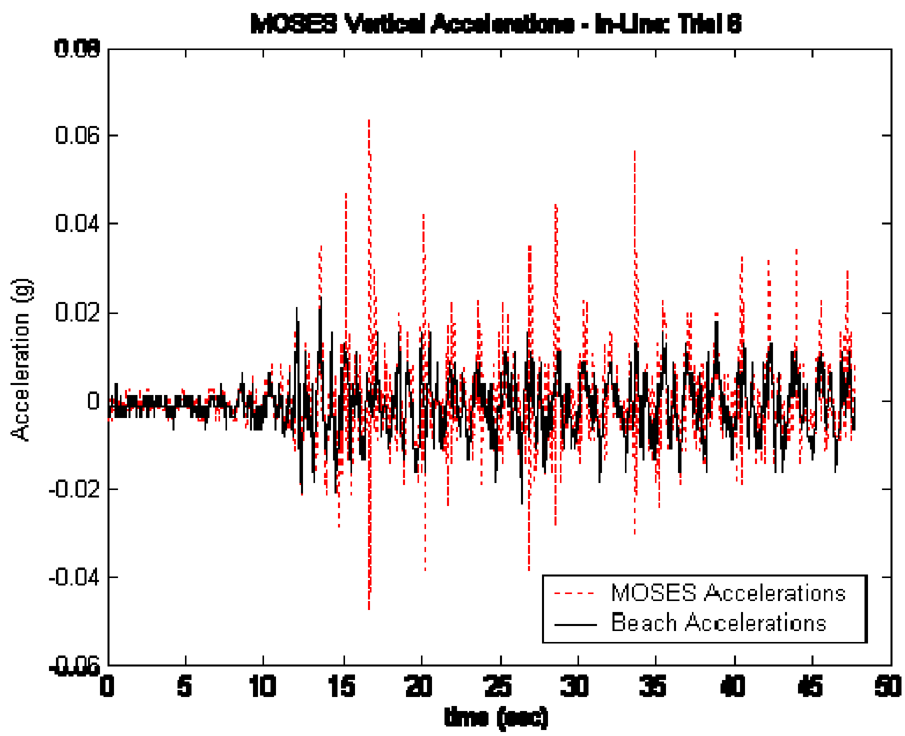


Figure 9: In-Line Vertical Accelerations

From the above figure, it can be seen that, although the beach does add significantly to the acceleration on the surface of MOSES, the bag experiences its own movements beyond the effect of the beach. Also to be noted is that the magnitude of the accelerations experienced on the bag did not exceed .06g or .6m/s^2 even with the accelerations caused by the beach included. Further research is needed to determine accelerations acceptable to tank and HMMVW drivers over a surface. However, from visual inspection of the bag movements, it would appear that this is an insignificant motion caused by the bag.

The second set of tests looked at MOSES angled at 40 degrees to the incoming wave crests. Both vertical and horizontal accelerations were recorded from this experimentation. Figure 10 shows the results from a typical 40-degree vertical acceleration test.

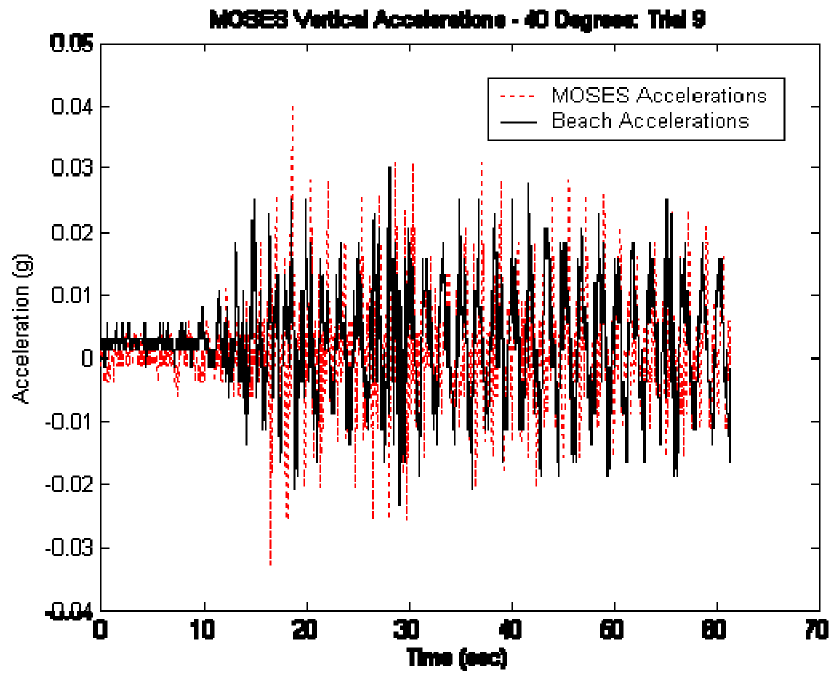


Figure 10: 40 Degree Vertical Accelerations

From the above plot, it can be seen that the vertical accelerations were nearly completely caused by the motions of the beach. The plot in Figure 11 shows the results from a typical 40-degree horizontal acceleration test:

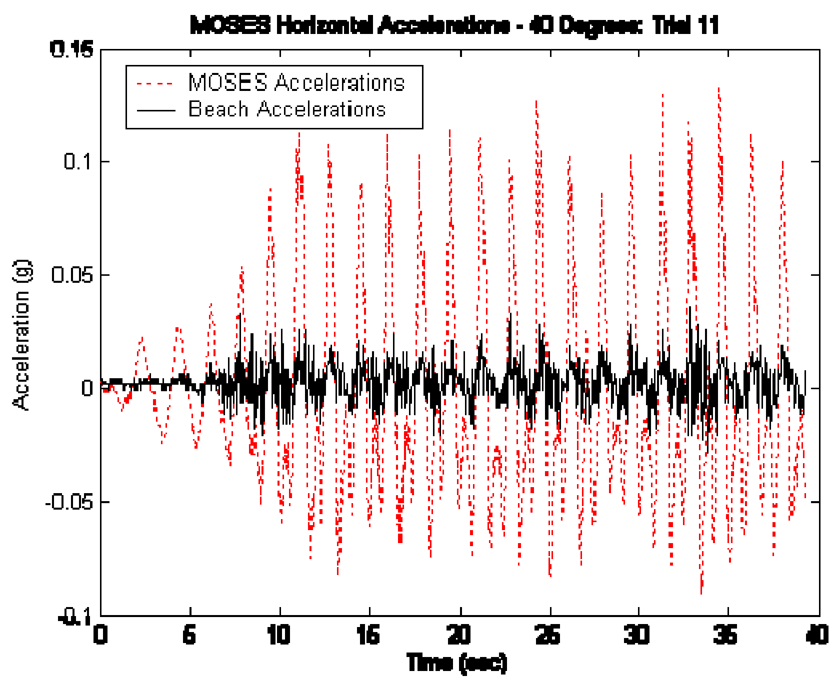


Figure 11: 40 Degree Horizontal Accelerations

The accelerometers were placed 3" above the surface of the bag, this translates to approximately the top of the reservoir walls of the full scale model. Peak accelerations are less than .15g or 1.5 m/s^2. If these magnitudes are unacceptable for the successful movement of equipment over the bag surface, it should be noted that there might have been a dynamic effect of the beach motions, which have not been seen, and further experimentation should be conducted.

The final set of tests conducted was for the bag perpendicular to waves. The motivation for this test was to observe the ability of an inflatable structure such as MOSES to double as a breakwater for other operations. In this experimental set-up, a capacitance probe wave height sensor was placed before and after the bag to measure the change in wave heights across the barrier. Additional motivation for this test was to confirm that the weight of MOSES was sufficient to maintain position in the worst case deployment. Figure 12 is typical of the wave attenuation characteristics of the MOSES model.

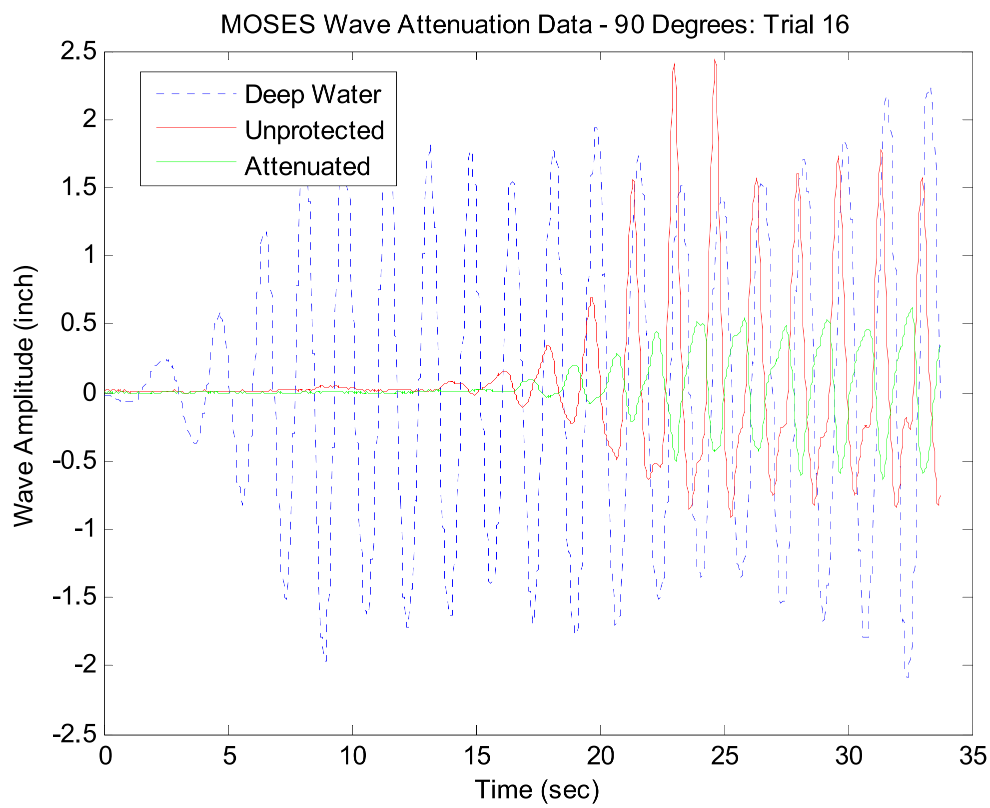


Figure 12: 90 Degree Wave Attenuation Results

It can be seen from the above plot that MOSES reduces the wave to nearly half of its original height. Without further research into the acceptable levels of attenuation, no conclusions can be made at this time.

Along with the quantitative analysis of the model testing experiments, some visual observations were made throughout the testing. The first observation was that the addition of the scaled weight of a tank on the surface of the bag did not add observable deflection to the bag surface. The second observation was that as the bag transitioned from the 1:20 to 1:50 slope and over a piece of 2”x4”, the bag conformed. The representation was found too rigid to be used effectively. Consequently, roadway tests were dropped.

Deployment Model

The initial deployment model was constructed on a plank of wood to simulate how erect the walls would be when the bag was fully inflated and rigid. It was shown through testing that the air beams required about 20 psi to inflate and stand upright. However, it was observed that the design of the 20 psi air beams was unable to support any significant amount of force and would prove incapable of holding a column of water or deflecting a wave.

In order to test how efficient the air beam system was at unrolling the bag, another model was constructed. This model was constructed with an air beam system similar to the first model except it had extra tubes that ran along a sheet of vinyl. These tubes were secured to the length of the sheet of vinyl and were used to simulate the longitudinal force that the full scale system would apply to the unrolling of the bag. It should be noted that in the full scale system the walls would run the entire length of the bag, and add an additional vertical force to the bag making it easier to unroll.

The rationale behind the deployment test was that if the air beam system could cause the bag to unroll, then it would not have a problem unrolling the rest of the system because the mass decreases as the bag unrolls. With this in mind, the model was constructed to have a sheet of vinyl with the air beam system connected to it, and at the end of the strip, a weight was placed to simulate the scaled weight of the entire rolled up bag. For ease of fabrication, the scaled model and all of its components represented half of the system meaning only one side of the wall was used and half of the weight of the bag scaled.

The test was demonstrated that the air beam system was able to unroll the scaled weight of the bag. Complications arose when the bag was not tightly rolled because the length of the air beam was somewhat shorter than the bag. This should not pose a problem in the full scale system because the walls will run the entire length of the causeway which will provide additional lift and assist in the unrolling process. Other than this minor issue, the air beam system was successful in deploying the bag. (See Appendix H)

3.0 Conclusion

The Navy requires a lightweight, rapidly deployable causeway system that can remain stable during high sea states. The MOSES causeway concept fulfills all these criteria and shows sufficient promise to warrant further development. Though more research is required on various components of the causeway, the results of the current model testing has proven to be invaluable in the continuing development of MOSES.

4.0 Recommendations

This year's team has recognized several key areas of work that need to be completed in order to take this project to the next level. Those key areas are: the air beam structure, attaching the air beams to the bag, the roadway, varying slopes, and testing on a static beach. After it was proven that air pressure was sufficient to erect the walls, it became evident that with the current model scale structural design of the walls would not stand up to any significant wave impact. It is suggested that a cross-member or truss design may improve the stability and rigidity of the walls, or it may even prove beneficial to use an arch type system rather than using right angles.

Another part of the causeway that needs investigation is the roadway on which the various vehicles would traverse. The main reasons the roadway was not investigated further were that the scaled weight was too great to be practical and at the scaled size the planks would be too small to effectively model performance. A different approach to the roadway portion of the causeway may be to find a lighter material, or use a different design approach altogether.

A major discrepancy in the water based model is that it was constructed with a uniform cross-section. The full scale causeway is tapered to contour to the slope of the seafloor, but there is an inherent problem with this idea; no two beach slopes are identical. A way to solve this problem may be to create MOSES to be split in sections, each with a different slope, so that joining the proper sections together can create the configuration needed to conform to a certain slope. This modular design is useful for dealing with the concern of varying slopes, but it presents its own challenges. With MOSES in sections it is no longer one solid rapidly deployable causeway because the slope has to be examined and the proper pieces need to be joined together, making for greater deployment time. Another issue with this design is that all the sections require storage space.

The most important issue that was observed during testing was that the beach that was constructed in the 140-foot basin would undulate as the waves traveled across it. To correct this, measurements of the movement of the beach were recorded and related to that of the MOSES. The ideal test would be to go to an actual beach to test, but then the problem arises of getting properly scaled waves in order to get relevant data.

5.0 References

Dickens, Kent, and Philip Rosen. 2007. *MOSES – Inflatable Causeway*. Ship Systems Integration & Design Department Technical Report. Naval Surface Warfare Center Carderock Division: West Bethesda, MD.

Lloyd, A.R.J.M., 1989. *Seakeeping: ship behavior in rough weather*. Ellis Horwood Limited: West Sussex, England

Appendices

Appendix A: CISD NREIP PROJECTS – SUMMER 2008 Initial Briefs

MOSES Demonstration

Introduction

1. The Summer 2007 MOSES project developed a water filled causeway suitable for the transfer of Main Battle Tanks and other vehicles from supply ships to the beach.

2. In order to develop this concept further it is necessary to assess the motions and deformations of the system in the surf zone, using a model scale demonstrator in the 140 foot model basin.

Aim

3. To identify the motions and deformations of a MOSES model prototype under surf zone conditions when loaded with Main Battle Tanks.

Design Requirements

4. Development of a physical model for experimentation that meets, at scale, the intentions of the original MOSES design concept, but remains compatible with the project resources and the capabilities of the 140 foot model basin with beach modifications.

Areas of Technology Exploration

5. Development of an appropriate scale model of the MOSES system suitable for use in the 140 foot model basin.

6. Reconfiguration of the model basin to allow quantitative and qualitative analysis

7. Addition of a representative "beach" to the model basin.

8. Qualitative and if possible quantitative identification of MOSES system motions and deformations under combined wave and vehicle loading.

Constraints

9. The model of MOSES shall be constructed by the design team and shall not require complex workshop support.

10. The model of MOSES shall be compatible with the model basin.

Approach

11. The team will review requirements and then brainstorm potential ideas.

12. A design for the model shall be developed and material requirements shall be identified. Materials shall be ordered and the model constructed.

13. The model basin shall be prepared for the experiment and a test plan identified.

14. The MOSES model experiment shall be undertaken and a report developed that details the findings.

Deliverables

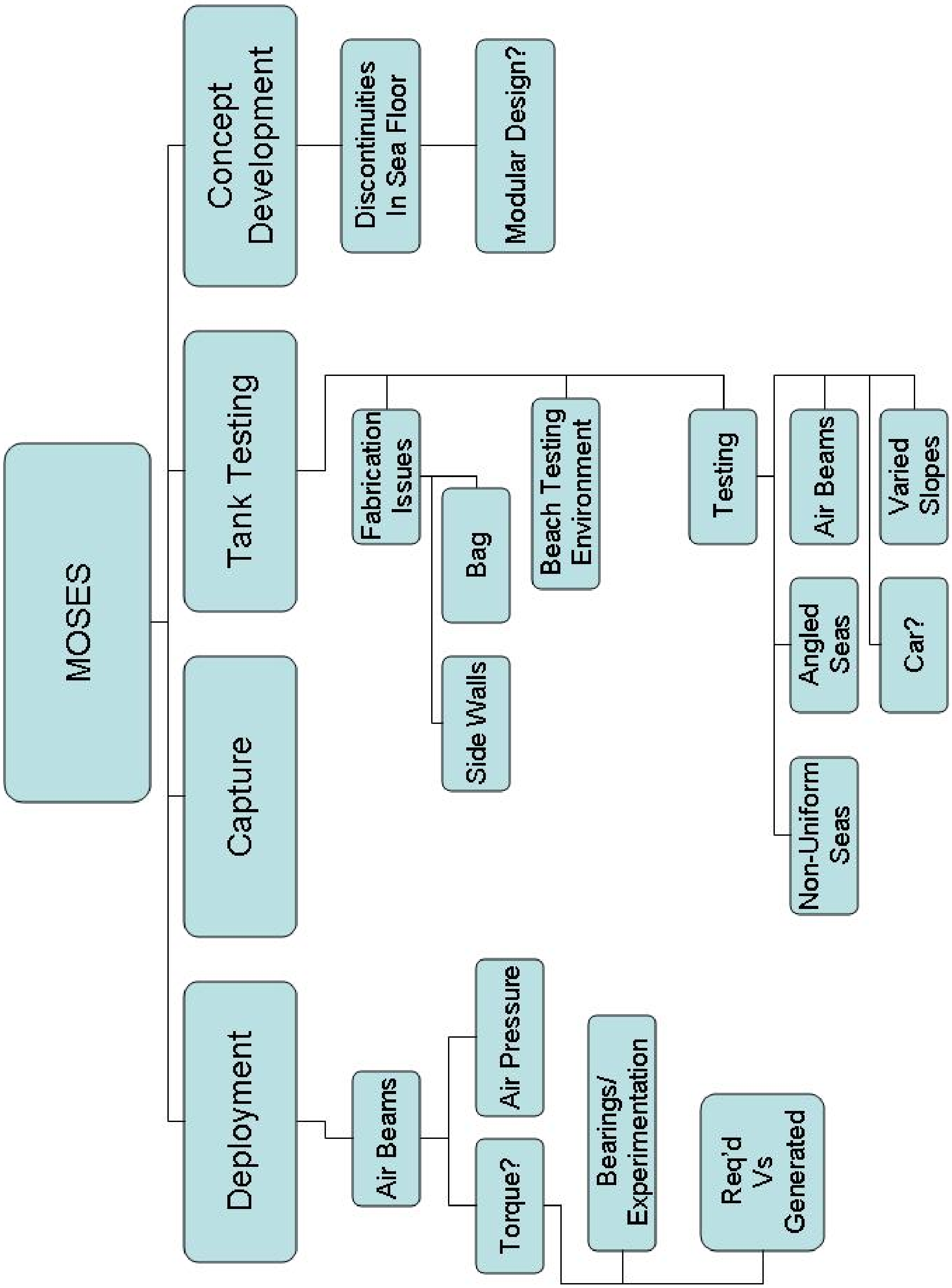
15. All work will be documented in a CISD Project Technical Report. The final report and presentation shall be suitable for unclassified, public release.

16. During the first 2 weeks the team will produce a team project plan of actions, assignments and milestones.

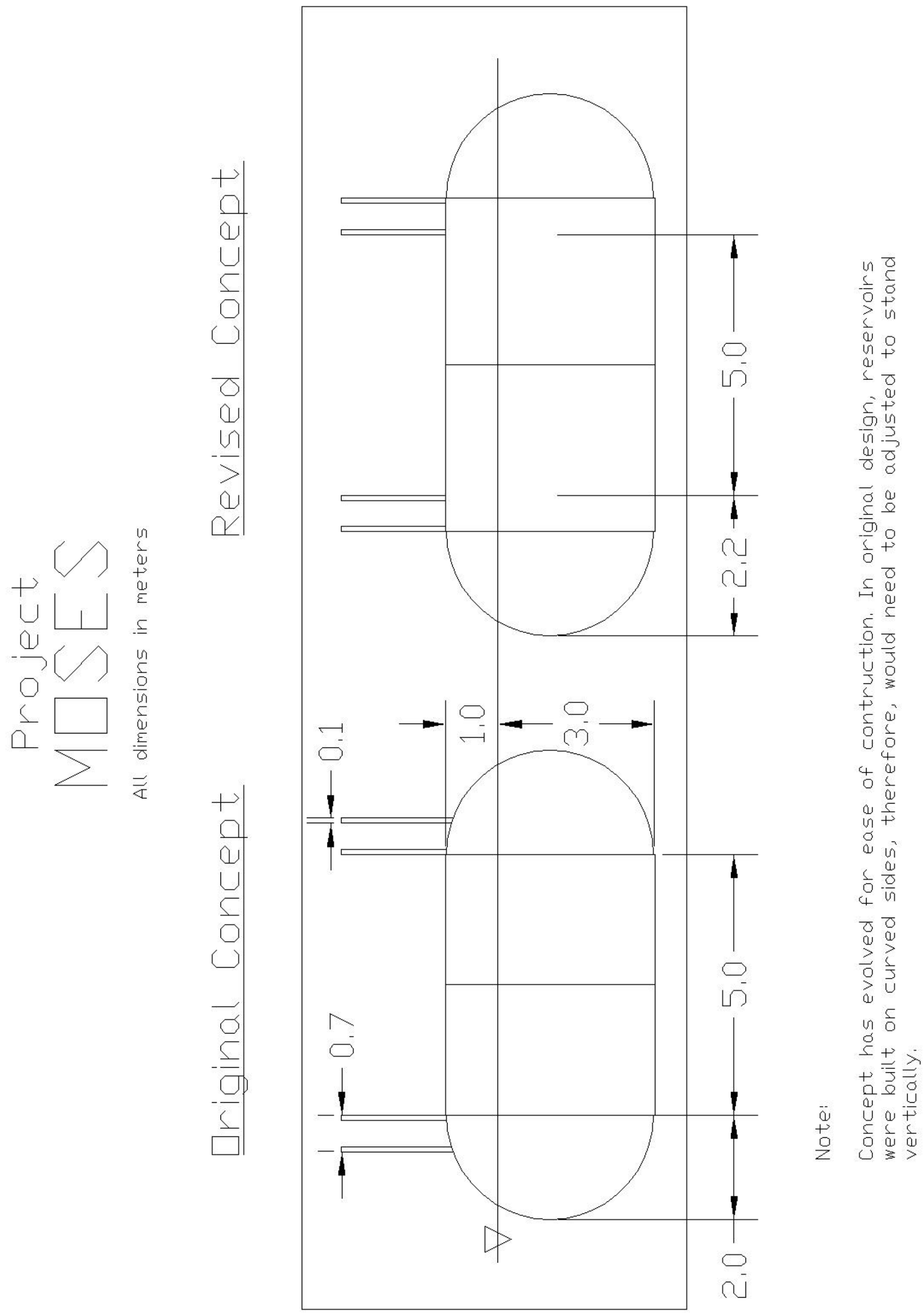
17. The team will develop and give informal intermediate presentations and a final project presentation.

18. The team will be encouraged to produce a technical paper from the final report that would be published at a professional society conference in the future.

Appendix B: 2008 MOSES Focus Results



Appendix C: MOSES cross section modification



Appendix D: 2007 Design

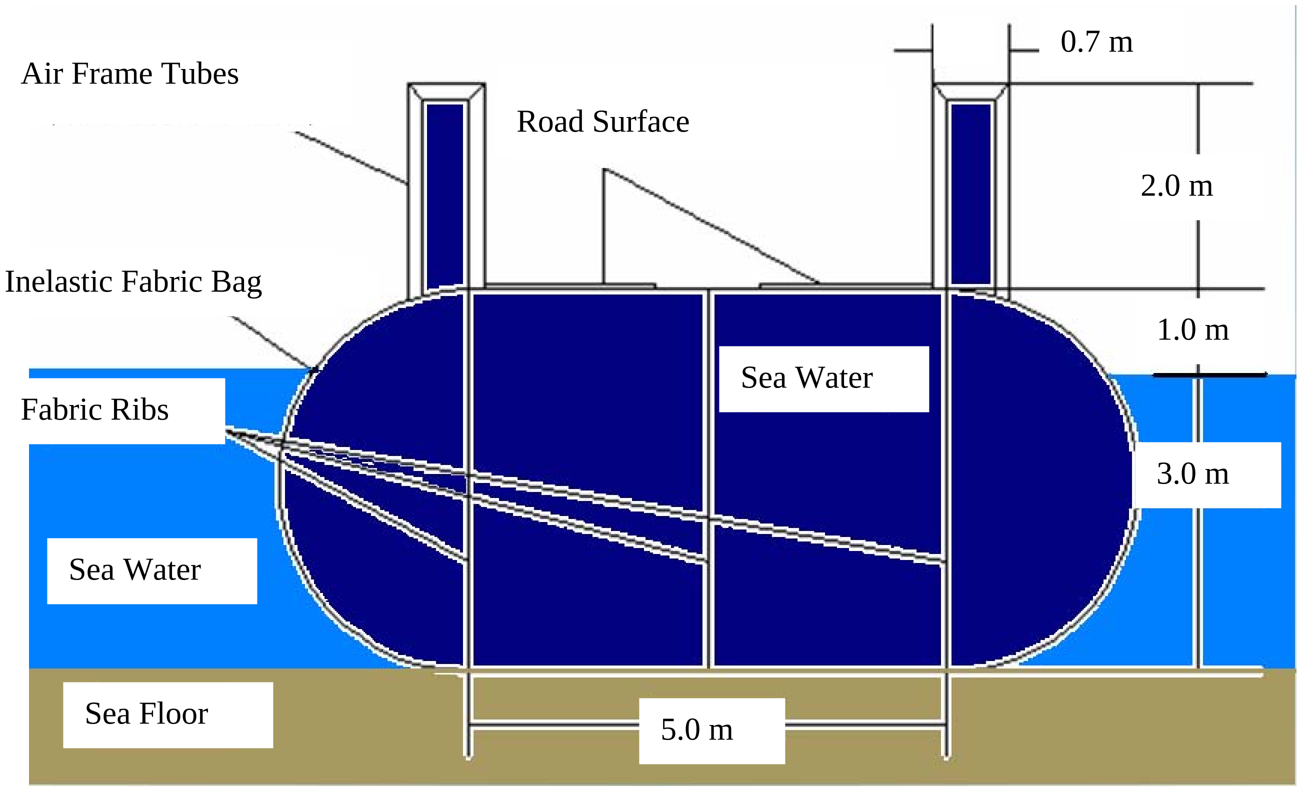


Figure 3: 2007 Concept Cross Section View

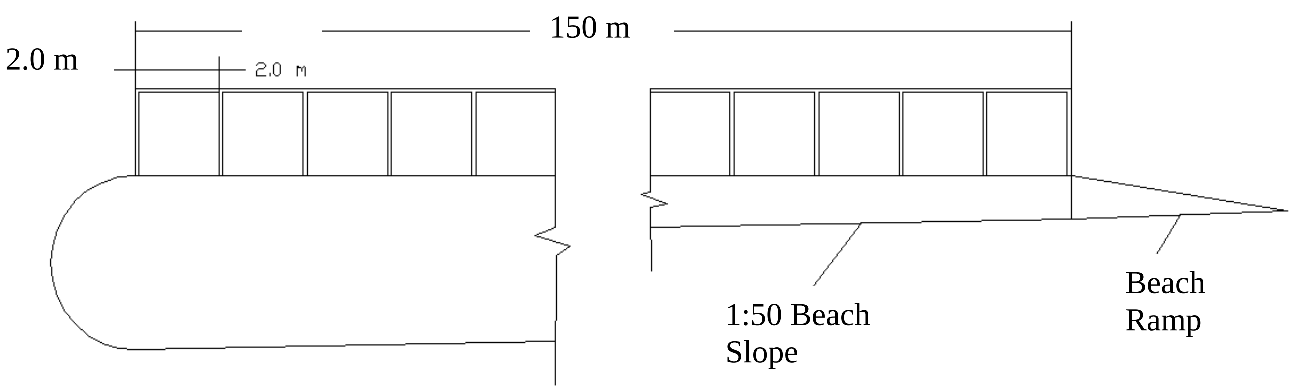
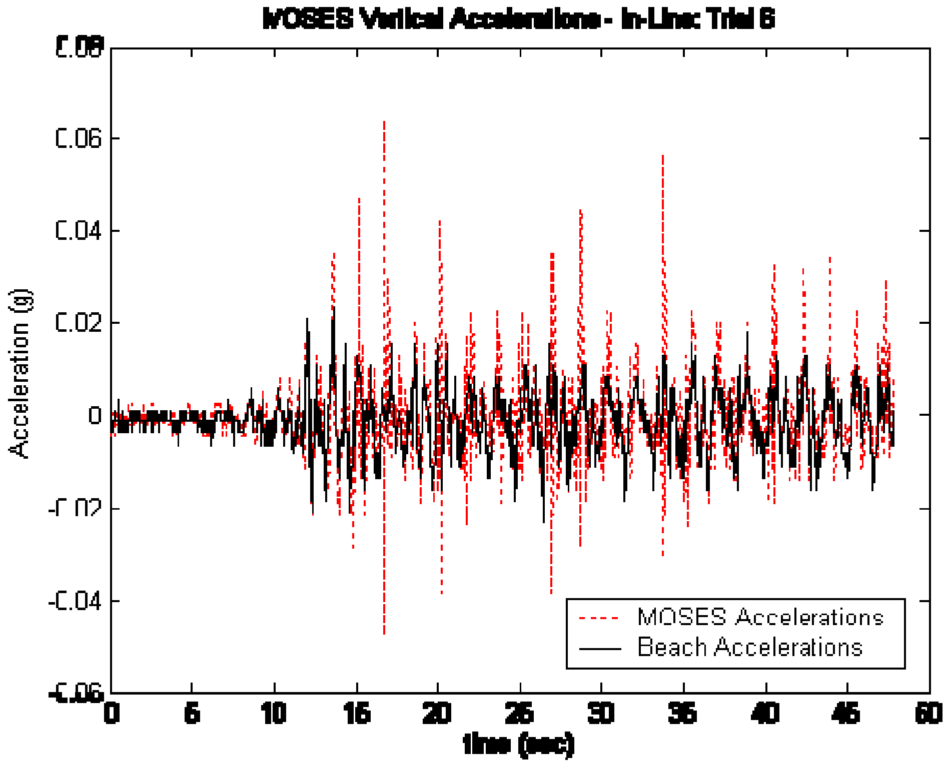
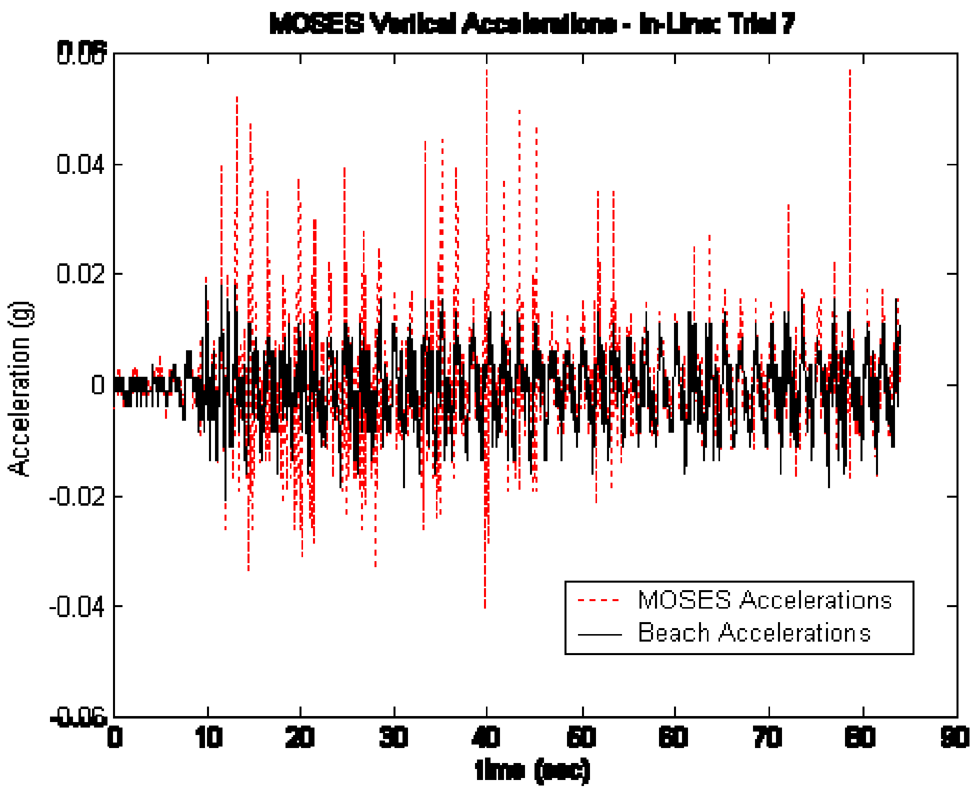


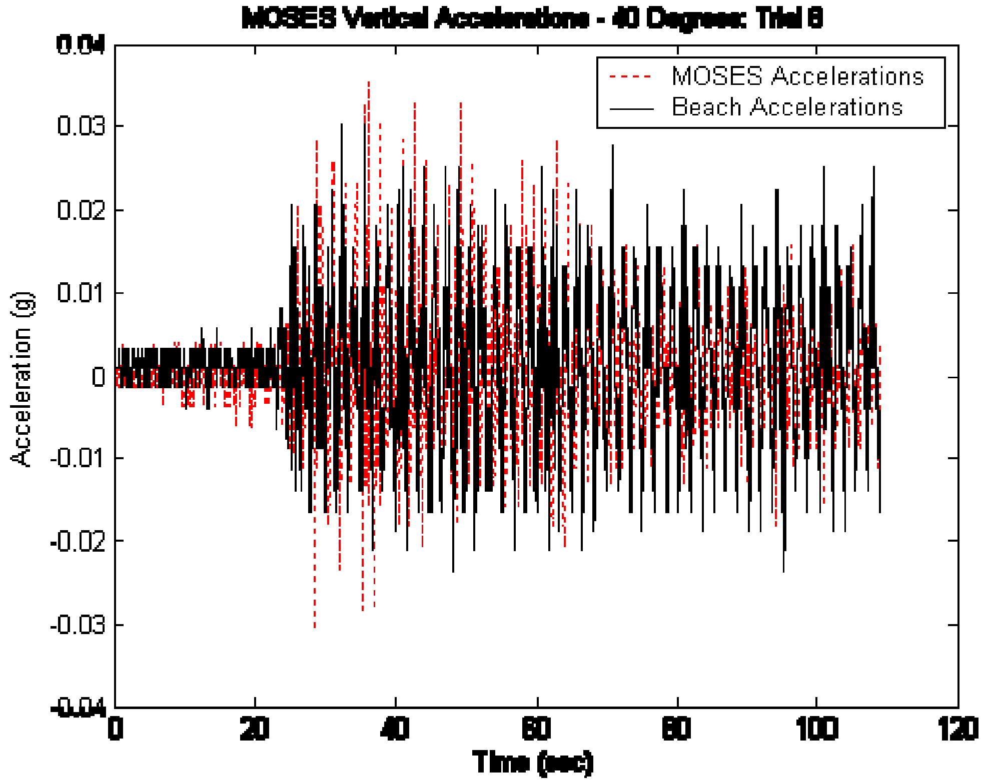
Figure 4: 2007 Concept Profile View

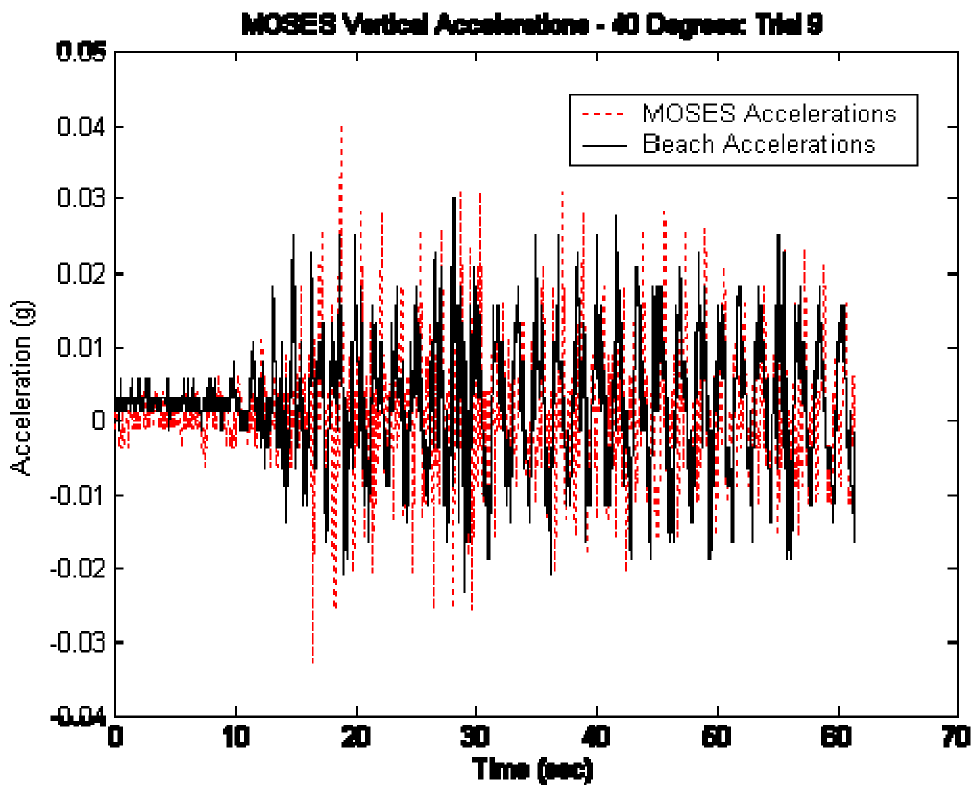
* Above figures from 2007 MOSES Project

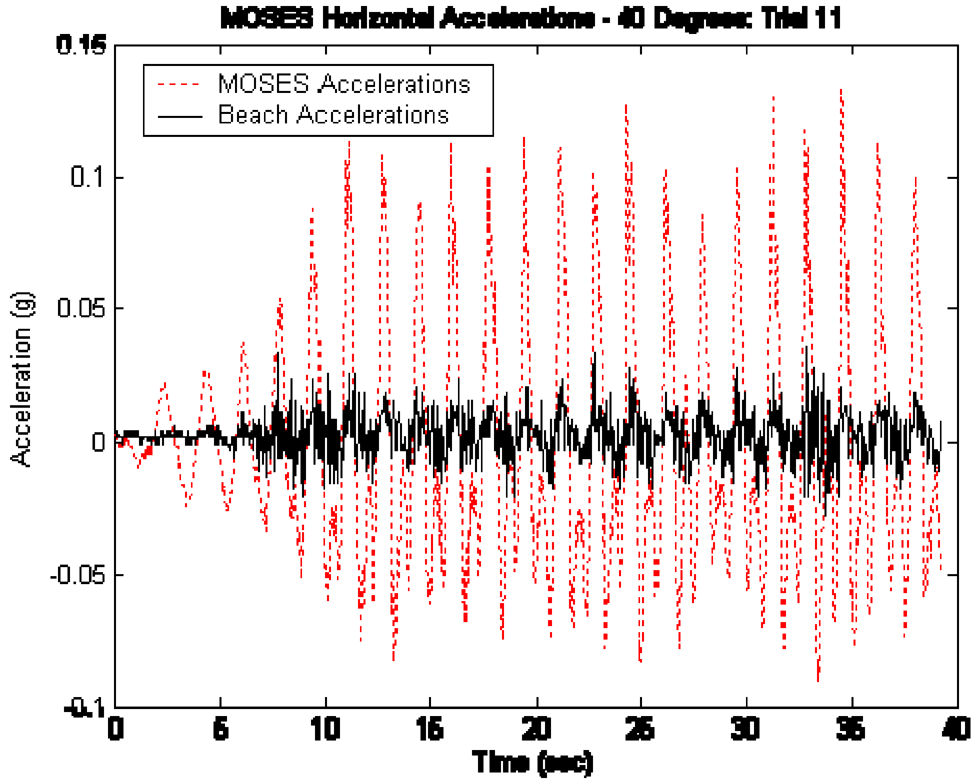
Appendix E: In-Water Experiment Results

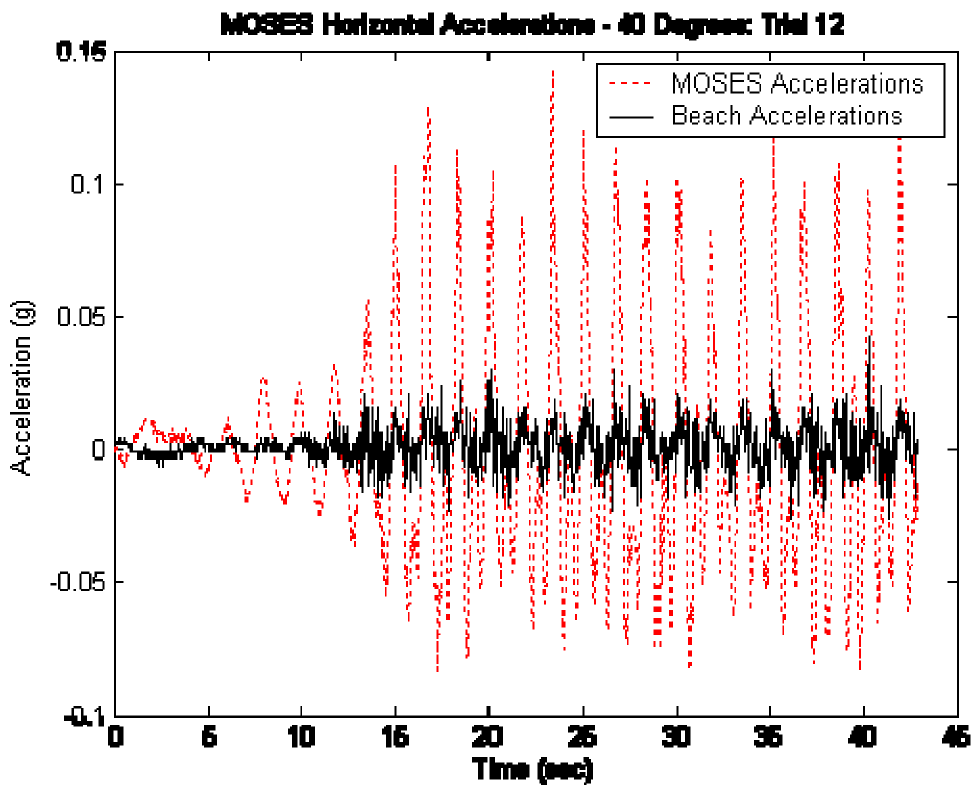


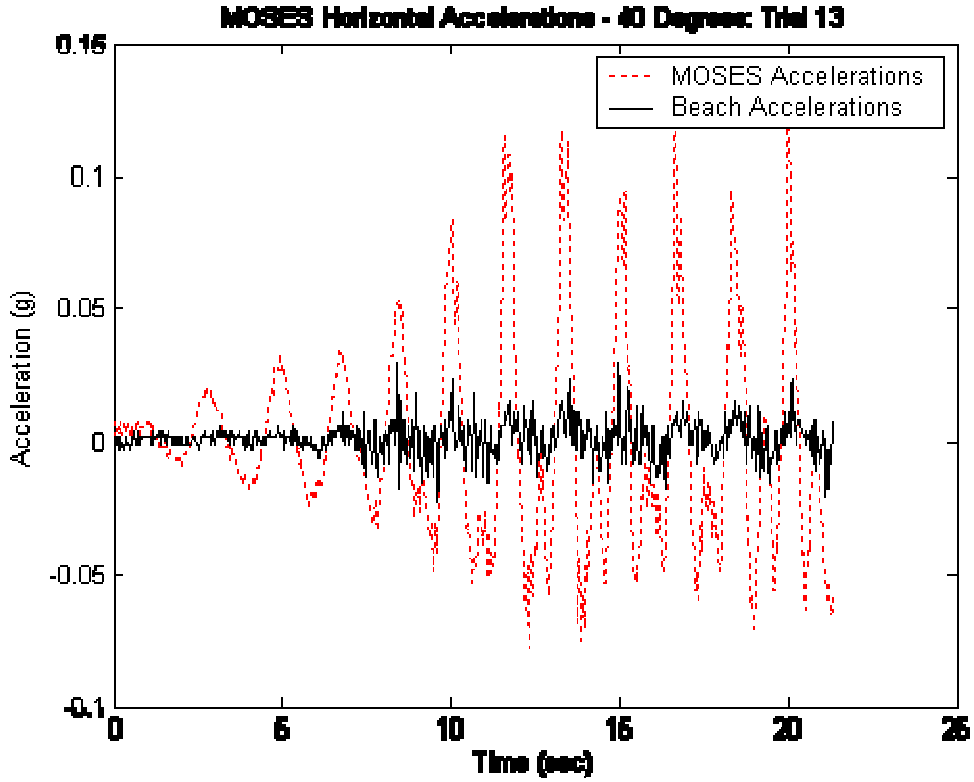


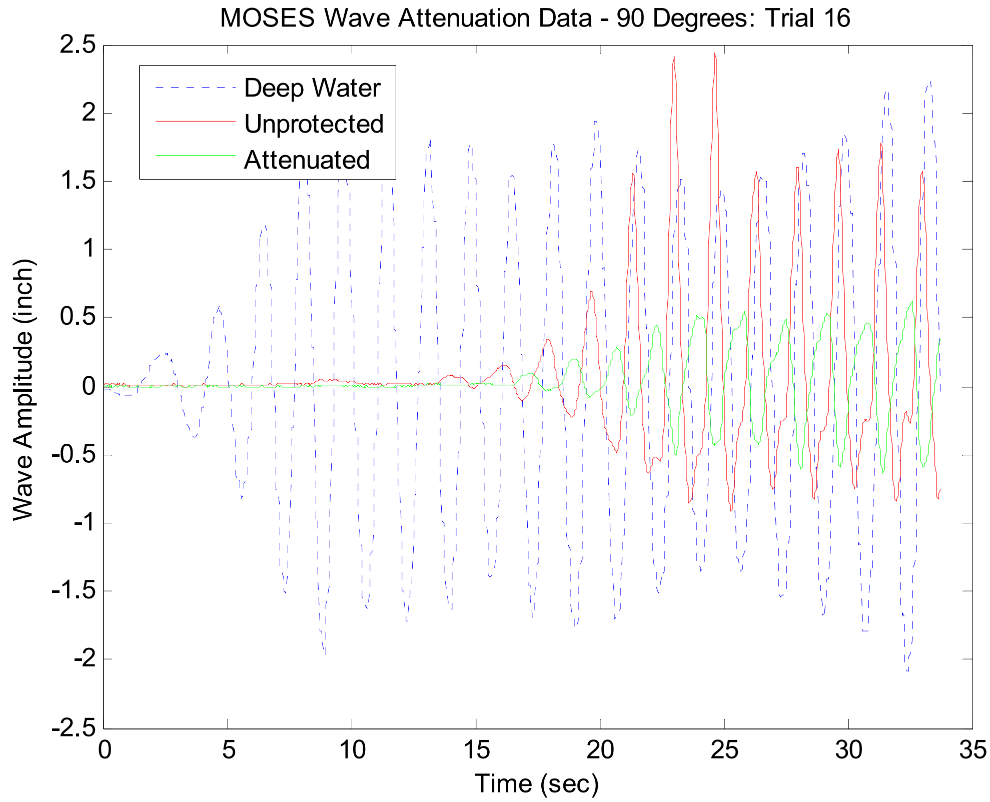

MOSES Vertical Accelerations - 40 Degrees: Trial 8
MOSES Accelerations
Beach Accelerations
Acceleration (g)
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
20
40
60
80
100
120
Time (sec)

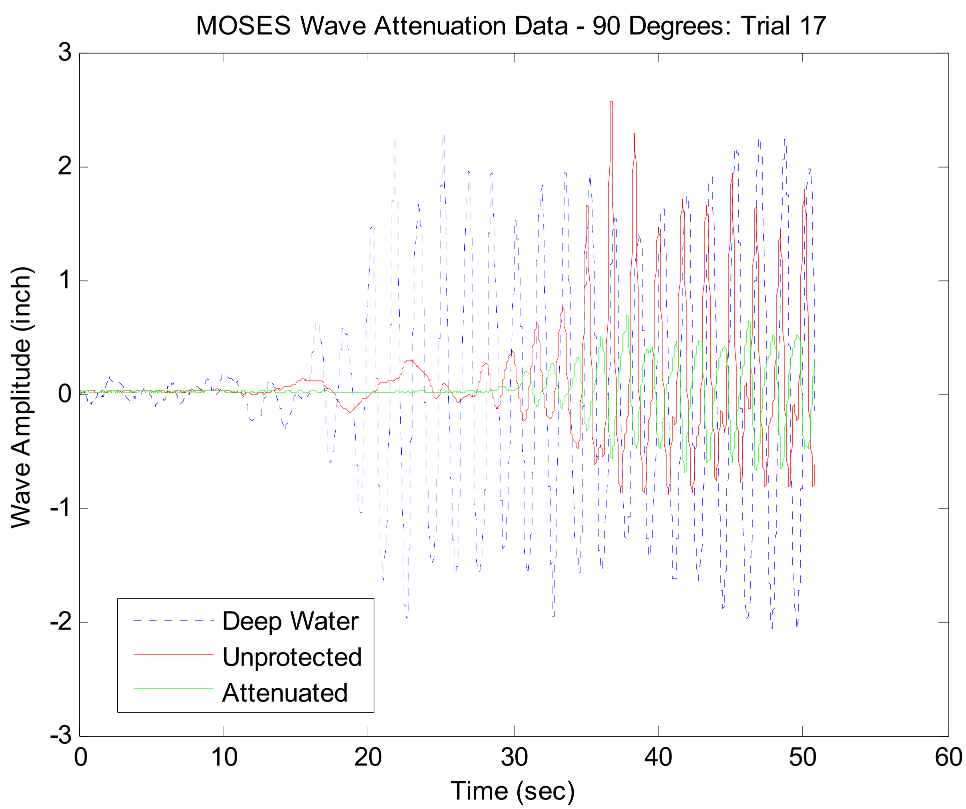

MOSES Vertical Accelerations - 40 Degrees: Trial 9
MOSES Accelerations
Beach Accelerations
Acceleration (g)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
10
20
30
40
50
60
70
Time (sec)

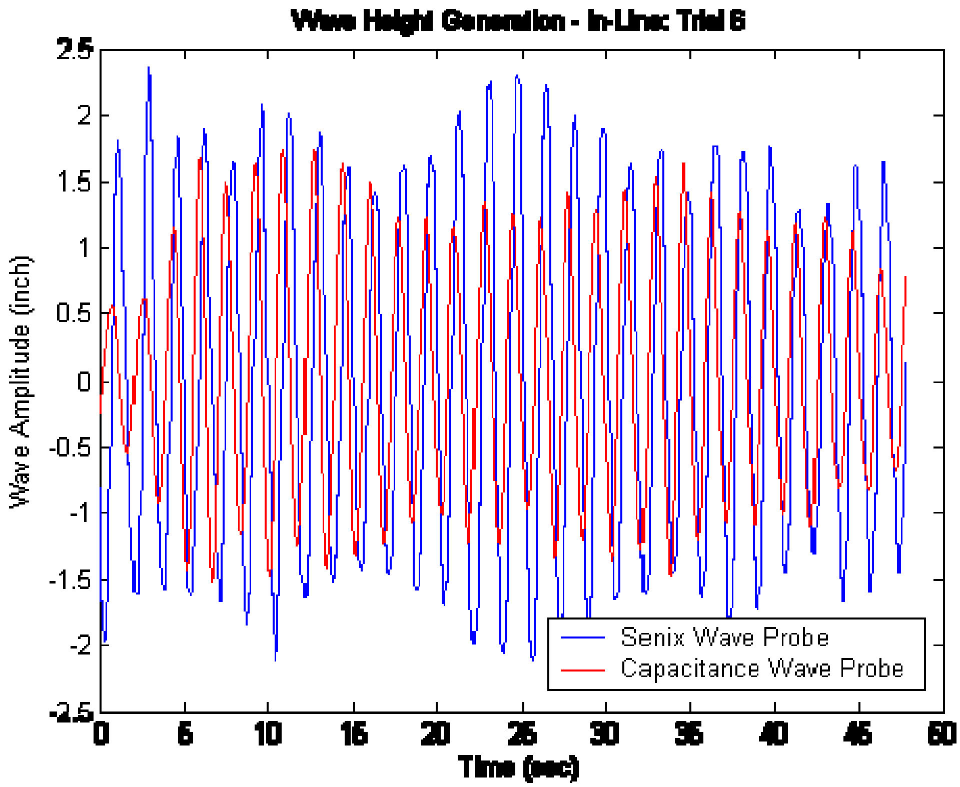

MOSES Horizontal Accelerations - 40 Degrees: Trial 11
MOSES Accelerations
Beach Accelerations
Acceleration (g)
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
30
35
40
Time (sec)


MOSES Horizontal Accelerations - 40 Degrees: Trial 12
MOSES Accelerations
Beach Accelerations
Acceleration (g)
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
30
35
40
45
Time (sec)

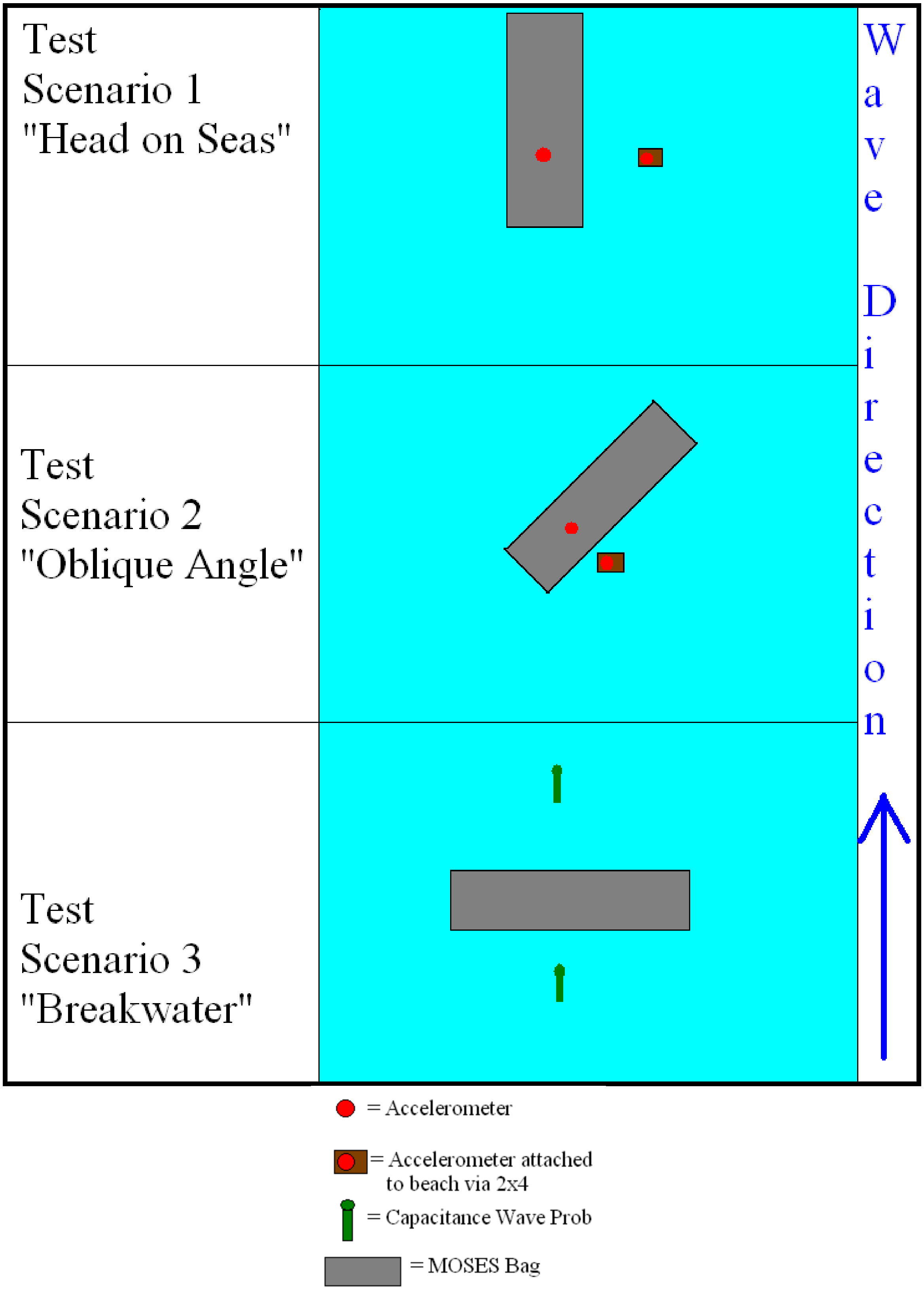

MOSES Horizontal Accelerations - 40 Degrees: Trial 13
MOSES Accelerations
Beach Accelerations
Acceleration (g)
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
Time (sec)


MOSES Wave Attenuation Data - 90 Degrees: Trial 16
Deep Water
Unprotected
Attenuated
Wave Amplitude (inch)
Time (sec)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
20
25
30
35

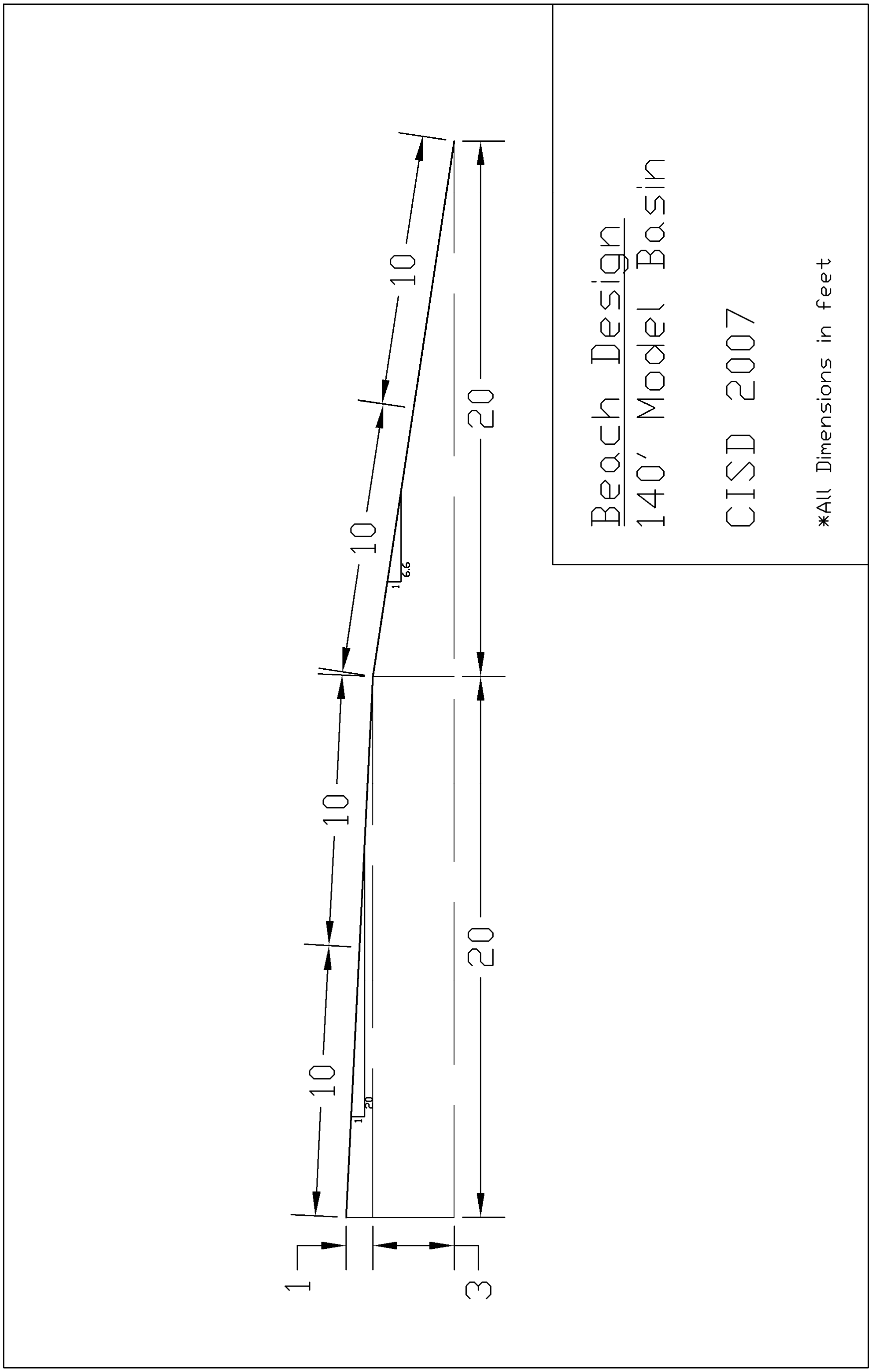

MOSES Wave Attenuation Data - 90 Degrees: Trial 17
Deep Water
Unprotected
Attenuated
Wave Amplitude (inch)
Time (sec)
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60


Wave Height Generation - In-Line: Trial 6
Wave Amplitude (inch)
Time (sec)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
20
25
30
35
40
45
50
Senix Wave Probe
Capacitance Wave Probe

Appendix F: Water Based Model Experiment Arrangement



Appendix G: In-Water Model Beach Profile



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